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In-situ biochar application conserves nutrients while simultaneously mitigating runoff and erosion of an Fe-oxide-enriched tropical soil

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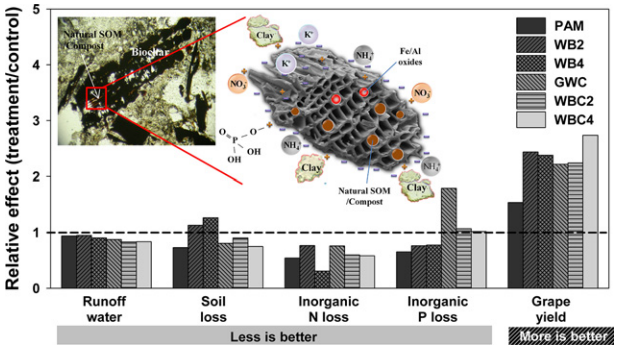
HIGHLIGHTS

- Co-applying biochar and compost notably reduced runoff and soil loss by 16%–25% in a tropical soil.
- In-situ biochar applying increased inorganic N, available P and K by 1.5–2.5 times in slopelands.
- Crop productivity was enhanced by biochar applying 1.5–2 times at least in a tropical slopeland.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change gives rise to rapid degradation of rural soils in sloping subtropical and tropical areas and might further threaten environmental sustainability. In this study, we conducted an integrated evaluation of the effects of wood biochar (WB) application mixed with a green waste dreg compost (GWC) on runoff quality, soil losses, and agricultural productivity for a highly weathered tropical soil. A conventional agriculture method, in which soils are treated with anionic polyacrylamide (PAM), was also conducted for comparison. The amounts of runoff and soil loss, and nutrient retention were evaluated a year after WB application. Soil fertility was also investigated through a year pot experiment with rape (*Brassica campestris* L.) cultivation. Our results showed that the WB application not only effectively increased soil pH, soil organic carbon (SOC) and exchangeable K^+ but also increased the production of rape plants. Significant reduction of runoff and the increases of inorganic nitrogen (IN) and total phosphorus (TP) were found in the WB-treated soil. Compared to the control, the co-application of WB and GWC, particularly for the WB at 4%, decreased runoff by 16.8%, soil loss by 25%, and IN loss (via runoff) by 41.8%. Meanwhile, compared to the control and PAM treatments, the co-application of WB and GWC improved soil acidity and the contents of SOC, IN, TP, and exchangeable K^+. The co-application of WB and GWC could be

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an alternative agricultural strategy to obtain benefits to agricultural productivity and environmental sustainability.

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1. Introduction

Over 73% of areas in Taiwan consist of slopelands, and most slopelands are used for agricultural purposes. Most of the rural soils of slopelands in Taiwan include colluvial sediments (Entisols and Inceptisols) and highly weathering soils (Ultisols and Oxisols) that commonly indicate poor soil fertility and quality. In humid subtropical or tropical climates, intensively cultivated slopeland soils are generally very acidic (pH ≤ 5.0), with low contents of soil organic carbon (SOC) (≤1%), cation exchange capacity (CEC), and base saturation percentage (BSP) (Hseu et al., 2014; Jien and Wang, 2013; Jien et al., 2015, 2017).

Farmers are mostly not aware of the vulnerability of their soils to degradation, especially in mountainous or slopeland areas, where unpredictable erosion causes irreversible damage to soil and environmental sustainability. Excess nutrients supplied to crops in those degraded rural soils can be released into water bodies through surface runoff and eroded sediment or leaching, also known as non-point source pollution, thereby reducing surface water and groundwater quality (Mailapalli and Thompson, 2011).

Losses of soil particles and nutrients via erosion from slopeland rural soils not only obviously depletes soil fertility, accelerates soil acidification, and increases fertilizer costs, but also adversely affects the quality of surface water and groundwater (Martínez-Mena et al., 2012; Otero et al., 2011). Pärn et al. (2012) mentioned that N and P are lost because of erosion by around 10–270 and 0.8–14.5 kg ha^{-1} y^{-1}, respectively, from slopeland areas under temperate climate, and these losses might be higher under subtropical/tropical climate. Soil and nutrient losses vary substantially depending on both rainfall intensity and soil properties, particularly of soil organic matter (SOM) and aggregate stability (Laird et al., 2010). Thus, the effective maintenance of SOM in slopeland soils can help preserve soil fertility and decrease susceptibility to erosion by enhancing aggregate stability and hydraulic characteristics (Auerswald et al., 2003; Tejada and Gonzalez, 2007).

In Taiwan, the application of anionic polyacrylamide (PAM) has been used as an effective method for reducing water turbidity and soil erosion. Application of PAM improves soil aggregation, infiltration rate, and water retention as well as reduces water turbidity and soil erosion (Busscher et al., 2007). However, its effectiveness can be limited depending on the soil properties, such as calcium level, clay content, electrolyte level, and SOM (Lee et al., 2010; Wu et al., 2012). The efficacy of PAM in fields has also been considered to be short-term. Therefore, an alternative application method in terms of the ecological aspect and sustainability should be developed for effective soil erosion control.

Biochar is a by-product derived from pyrolysis of organic wastes, serves as a pool of chemically/biologically stable carbon (Lehmann et al., 2009). Numerous studies have reported that biochar is an effective resource for improving the physicochemical properties of soils, including their SOM, aggregate stability, nutrient efficiency, and crop productivity, particularly in long-term cultivated soils under subtropical and tropical climates (Chan et al., 2007; Deenik et al., 2011; Jien and Wang, 2013). Furthermore, the application of biochar to soils has been considered a practical method for the long-term maintenance of SOC and fertility.

Yuan and Xu (2011) demonstrated that fertilizer-use efficiency and crop yield increase following biochar incorporation. The employment of biochar in highly weathered tropical soils has been determined to effectively enhance soil quality and physical properties (Jien and Wang, 2013; Laird et al., 2010). Jien and Wang (2013) and Hseu et al. (2014) reported that biochar application could effectively reduce soil loss by >40% in a highly weathered soil and a mudstone soil in Taiwan, respectively.

Recently, co-composting or co-application of biochar and other organic amendments has been identified as an excellent management practice by compensating for the limitation of each amendment (Awad et al., 2012, 2013; Rogovska et al., 2011; Sanchez-Monedero et al., 2017).

The objectives of this study were to investigate the effects of PAM, biochar, compost, or various mixtures of such on the physical and chemical properties of highly weathered slopeland soils and to evaluate the effects of PAM and organic amendments on plant growth, runoff, soil loss, and nutrient retention under natural rainfall conditions.

2. Materials and methods

2.1. Study site

The experiment was conducted in the international standard soil erosion plot having a slope of 9% near the National Pingtung University of Science and Technology in Southern Taiwan (E 120° 36′ 22.38″, N 22° 38′ 41.43″) for a year (July, 2014 to June, 2015). For this region, the average annual temperature and precipitation are 24 °C and 2847 mm y^{-1}, respectively, and ~90% of annual precipitation occurs from May to September. The soil is classified as Typic Paleudults (Soil Survey Staff, 2014).

2.2. Treatments

A series of field subplots (1 m by 4 m) were used in this study, either without treatment (control) or with six soil treatments including: 1 kg ha^{-1} PAM (PAM), 2% wood biochar (WB; WB2), 4% wood biochar (WB4), 1% compost (GWC), 1% compost + WB2 (WBC2), and 1% compost + WB4 (WBC4). The relevant application levels are given as percentages (w w^{-1} on dry weight basis) of the bulk topsoil (20-cm deep). The subplots were vertically arranged on the slope with a randomized complete block design (RCBD). Before the experiment was performed, the subplots' initial vegetation was completely removed, and the topsoil was tilled, after which water was sprayed to reach the water holding capacity of the soil. The soil was then covered with canvas for a month, after which the treatments were administered.

For the PAM treatments, commercially available granular anionic PAM, having a high molecular weight of 12 mg mol^{-1}, was dissolved in deionized water to a concentration of 10 mg L^{-1}. The pH of the PAM solution was approximately 8.0. A 40-L PAM solution was then evenly sprayed on the soil surface of each PAM subplot, which equaled an application rate of 100 mg PAM m^{-2} (or 1 kg PAM ha^{-1}). The biochar used in this study was produced from driftwood, mainly zelkova, under anaerobic conditions at the pyrolysis temperature of 400 °C in the Industrial Technology Research Institute of Taiwan, as recommended by Lehmann (2007). The biochar was ground to pass through a 5-mm sieve and then well mixed. The compost used in this study was a commercial product, produced mainly from soybean meal, rice husks, fish bone meal, and green waste ash. After the amendments were well mixed with the topsoils, all the subplots including the control were covered with canvas and preincubated at their water holding capacity for a month.

2.3. Soil erosion and nutrient runoff experiment

The erosion experiment was conducted in the preincubated subplots under natural precipitation conditions for a year (July 1, 2014 to June 31, 2015). During the erosion experiment, weeds were removed every week by hands, and the temperature and precipitation were recorded daily. Fig. 1 illustrates the monthly rainfall. The runoff water was collected from each 4 m^2 subplot for the measurements of runoff, suspended solids, and released nutrients after filtration through a 0.45-μm filter membrane. Sediments were also collected and weighed after oven-drying at 50 °C.

2.4. Pot experiment

To identify the residual effects of the treatments on soil productivity after the soil erosion experiment was completed, the subsamples of the topsoils were collected from each subplot of the pot experiment. Five subsample points were defined, and a total of 3 kg topsoil was collected from each subplot. Then, the collected soil samples were air-dried, 2-mm sieved, and repacked into a 1/5000 a Wagner pot. After germination, one seedling of rape (*Brassica campestris* L.) was transplanted into each of the pots. The soil moisture was adjusted and maintained at 70% of the water holding capacity during 4 weeks of cultivation, and when weeds were identified, they were cut and reincorporated into the soil. At the end of the cultivation period, the rape shoots were harvested and weighed after drying at 65 °C for 3 days, and further analyses were performed.

2.5. Sample analyses and statistics

The soil texture was determined using a hydrometer (Gee and Bauder, 1986). The soil pH value was measured at 1:2.5 (w v^{-1}; McLean, 1982). Soil analyses were performed for organic carbon (OC) using the Walkley-Black method (Nelson and Sommers, 1996), total nitrogen (TN) using the modified Kjeldahl digestion method (Bremner, 1996), and exchangeable cations and cation exchange capacity (CEC) using the NH_4OAc leaching method (Rhoades, 1982). The total carbon (TC) was determined by heating at 550 °C (Nelson and Sommers, 1996), and the soils' inorganic N (IN) was extracted using a KCl solution (Mulvaney, 1996). The Bray P-1 of the soils was also analyzed (Kuo, 1996). The concentrations of N, cations, and P in the digested solution, extracts, leaching solutions, and runoff water were analyzed using a Kjeldahl-N distilling instrument, a flame atomic absorption spectrophotometer, and an ion chromatograph (ICS-1100, Thermo Fisher Scientific Inc.), respectively. Aliquots of the grounded plant sample (0.2 g dry weight) were digested using concentrated H_2SO_4 and 30% H_2O_2 at 250 °C for 30 min (Jones and Case, 1990). The concentration of N in the digested solution was measured using the semi micro-Kjeldahl procedure (Bremner, 1996; Mulvaney, 1996). Data were analyzed using ANOVA, and the treatment means were compared using least significant difference tests at a 0.05 significance level.

3. Results and discussion

3.1. Properties of soil, compost, and biochar

Table 1 presents the main properties of the soil, compost, and biochar used in this study. Briefly, the soil was strongly acidic (pH 4.5) and contained a low level of OC (0.91%), which is common in humid tropical regions. The low CEC of the studied soil was most likely caused by the low SOM content and low clay activity of the highly weathered soil. The pH values of the compost and biochar were 5.9 and 6.9, respectively, and their TC contents were 84% and 41%, respectively. The compost contained higher TN than the biochar did. The C:N ratio of the biochar was 112, which was considerably higher than that of the compost.

3.2. Soil and nutrient losses through runoff

The heavy annual rainfall (>2500 mm y^{-1}) in the study area can expose the soil to intensive leaching and soil erosion. The monthly precipitation during the experiment period is illustrated in Fig. 1 and indicates that heavy rainfall events were concentrated in July, August, and September of 2014 and in May of 2015. The chemical properties of soil loss and runoff are presented in Table 2. During the experiment, applications of most of the amendments significantly decreased the runoff under natural rainfall conditions ($P < 0.05$). The co-application of WB and GWC was the most effective in decreasing the runoff (by 16.7%). SOM can strengthen the soil aggregates with relatively large soil pores, which increases water infiltration rate and hydraulic conductivity (Lado et al., 2004a, 2004b; Tejada and Gonzalez, 2007). The biochar-involved treatments showed that biochar application, either with or without compost, was most likely to decrease water runoff and improve water conservation (Beck et al., 2011; Sadeghi et al., 2016) and indicated a similar or higher efficiency compared to the PAM application.

In general, less runoff water leads to less soil erosion. In comparison with the control, the amount of soil loss was significantly lower for the PAM, GWC, and WBC4 treatments; however, no significant difference was found among them (Table 2). This result revealed that the application of compost, as a natural treatment, could protect soil from water erosion with the same efficiency as PAM application, and previous studies showed that biochar treatment had the same protective efficiency under ordinary rainfall events (Hseu et al., 2014; Jien and Wang, 2013; Jien et al., 2015, 2017; Li et al., 2017). Our previous study has revealed that the driftwood biochar application into the same soil used in this study can improve soil physical properties including bulk density,

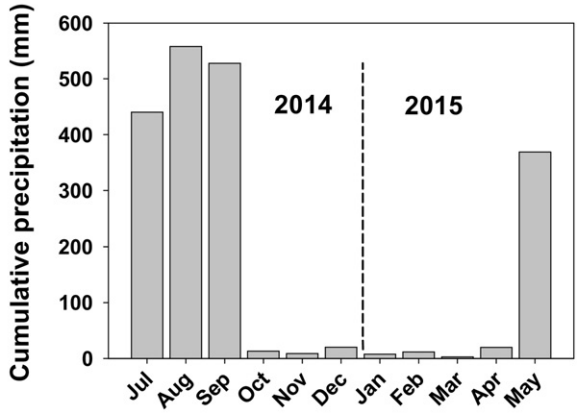

Fig. 1. Monthly precipitation during the erosion experiment.

Table 1
Selected properties of the materials used in this study.

Property	Soil	Biochar (WB)	PAM	Compost (GWC)
pH (1:2.5)	4.5	6.9	8.0	5.9
Sand (%)	34.0	–	–	–
Silt (%)	27.6	–	–	–
Clay (%)	38.4	–	–	–
CEC (cmol(+) kg^{-1})	14.5	23.2	–	78.3
TC (g kg^{-1})	9.1	413	822	843
TN (g kg^{-1})	0.64	3.7	–	47
C/N ratio	14	112	–	18
Inorganic N (mg kg^{-1})	43.4	187	–	453
Exchangeable Ca (mg kg^{-1})	105	940	–	242
Exchangeable Mg (mg kg^{-1})	2.56	57.2	–	75
Exchangeable K (mg kg^{-1})	49.3	88.7	–	15,700

Values shown are means ($n = 3$). The variation can be ignored when the coefficients of variation are <10%.

Table 2
Runoff water, soil loss, and runoff water IN content during the 1-year experiment.

Treatment	W_{runoff}	Soil loss	NH_4^+-N_{runoff}	NO_3^--N_{runoff}	P_{runoff}
	mm	kg m^{-2}	g m^{-2}	g m^{-2}	mg m^{-2}
Control	382 ± 5.8^{a}	15.5 ± 0.04^{bc}	1.41 ± 0.03^{a}	1.82 ± 0.30a	6.81 ± 0.64^{b}
PAM	358 ± 9.8^{bc}	11.3 ± 3.98^{d}	0.74 ± 0.57^{bc}	1.01 ± 0.90^{bc}	4.44 ± 0.04^{d}
WB2	362 ± 4.8^{b}	17.5 ± 1.14^{ab}	1.03 ± 0.06^{ab}	1.44 ± 0.31^{ab}	5.19 ± 0.32^{c}
WB4	345 ± 3.2^{cd}	19.6 ± 1.15^{a}	0.43 ± 0.19^{c}	0.56 ± 0.12^{c}	5.27 ± 1.18^{bc}
GWC	334 ± 6.3^{de}	12.5 ± 0.57^{d}	1.04 ± 0.57^{ab}	1.41 ± 0.24^{ab}	12.2 ± 0.20^{a}
WBC2	318 ± 2.7^{e}	14.0 ± 0.89^{cd}	0.84 ± 0.29^{bc}	1.09 ± 0.18^{bc}	7.27 ± 0.37^{b}
WBC4	319 ± 2.2^{e}	11.6 ± 1.98^{d}	0.84 ± 0.10^{bc}	1.04 ± 0.00^{bc}	6.93 ± 0.56^{b}

Values shown are means ± standard deviations. Individual letters after the means indicate no significant difference between the corresponding treatments ($P < 0.05$).
Control: without any amendment. PAM: application of 1 kg ha^{-1} PAM. WB2 and WB4: biochar application of 2% and 4%, respectively. GWC: compost application of 1%. CB2 and CB4: co-application of compost (1%) and biochar (2% and 4%, respectively).

saturated soil hydraulic conductivity, and mean weight diameter of soil aggregates during an incubation experiment (Jien and Wang, 2013). However, soil loss was significantly higher when WB4 treatment was applied, compared to the control (Table 2). The biochar was found floating in the runoff water during severe precipitation events and thus caused observable loss from the subplots (unquantified), even though the biochar had been well mixed with the topsoil. Furthermore, stronger splash erosion and sheet erosion were observed in the WB2- and WB4-applied subplots than in the other subplots. This may be explained by the stronger floating and hydrophobicity of biochar than of soil particulates and compost. The negative effect of biochar on soil erosion was not found under the co-application treatments with compost (WBC2 and WBC4). Doan et al. (2015) also reported that under natural rainfall, co-application of biochar with vermicompost resulted in the lowest soil loss compared with individual application of other organic matter or biochar. For best results, the biochar should be co-applied to a soil with other organic matter resources to protect the soil from water erosion under intensive precipitation events.

All treatments decreased the total IN loss through runoff, except for the WB2 and GWC treatments (Table 2). The N loss decreased from 3.23 to 0.99 g m^{-2} via the WB4 treatment compared with the control. Compost application resulted in the highest P loss amount, 12.2 mg m^{-2}, through runoff. Only the PAM and WB2 treatments significantly decreased the P loss level. On the other hand, the compost increased soil nutrients to a higher level, thereby increasing their leaching via runoff. Compost itself can be a source of nutrients, which can directly transport along with or release nutrients into the runoff water. Therefore, while GWC treatment significantly decreased both of runoff water and soil loss, the inorganic N loss via runoff remained statistically the same and P loss was even higher than that of Control. Biochar, however, normally contains less N and P than compost. Thus, biochar applied to soils can adsorb more nutrients, retain more soil water, and consequently decrease nutrient losses from runoff, as shown in Table 2. The co-application of biochar and compost resulted in less IN and P loss through runoff compared with the control, whereas the sole application of compost had no significant effect on the IN loss and even increased the P loss during the experiment. The similar result of co-application of biochar and vermicompost was also revealed by Doan et al. (2015).

3.3. Soil properties affected by the amendments after the erosion experiment

Chemical analysis was performed after the 11-month erosion experiment (Table 3). Compared with the control, the application of PAM or biochar alone and the co-application of biochar and compost resulted in significantly higher soil pH. There was no difference in soil pH between the GWC and control. Although PAM had the highest pH among all the amendments (Table 1), the pH of the PAM-treated soil was higher by only 0.2 compared with that of the control. The WB4 treatment resulted in the highest soil pH of 6.2, which is a higher value than that of the control by 1.4. These results were in line with those of previous studies, which reported that biochar is usually alkaline, possibly having a liming effect in the soils (Laird, 2008; Sandhu et al., 2017; Yuan and Xu, 2011). Because the compost did not significantly affect soil pH, the biochar most likely governed the pH change in the highly weathered and acidic soils.

Application of PAM did not change the SOC, whereas all other treatments significantly increased it compared with the control ($P < 0.05$). The highest SOC content of 1.27% was detected in the soil treated with the WBC4. This means that a significant amount of C was lost owing to decomposition, soil loss, runoff, and leaching in comparison with the 5% C added into the soil via WBC4 application. The co-application of biochar and compost is likely to retard the decomposition of C from either biochar or compost in a subtropical soil (Jien et al., 2015, 2017). The net increase in OC caused by an amendment could be identified as the OC content of a treated soil minus that of the control. In this study, the net increase in OC under the WBC4 treatment was 4.4 g kg^{-1}, which was even higher than the summation of those under the WB4 and GWC treatments (3.5 g mg^{-1}). The co-application of biochar and compost resulted in a net increase in OC approximately 28% higher than that expected (calculated from the individual application results), which implies a protective effect on the added carbon and corroborates

Table 3
Chemical properties of the soil sampled at the end of the soil erosion experiment.

Treatment	pH	OC	TN	Inorganic N	Bray-1 P	Ex. K
		%	g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Control	4.8 ± 0.0^{f}	0.83 ± 0.05^{d}	1.17 ± 0.10^{b}	81 ± 5.78^{d}	1.96 ± 0.03^{b}	52.4 ± 1.84^{d}
PAM	5.0 ± 0.0^{e}	0.85 ± 0.02^{cd}	1.16 ± 0.07^{b}	104 ± 0.00^{d}	1.54 ± 0.05^{c}	43.1 ± 0.88^{e}
WB2	5.5 ± 0.0^{d}	0.92 ± 0.05^{c}	1.20 ± 0.01^{b}	110 ± 11.6^{d}	1.93 ± 0.06^{b}	48.7 ± 4.35^{de}
WB4	6.2 ± 0.1^{a}	0.99 ± 0.04^{b}	1.18 ± 0.08^{b}	95 ± 8.66^{d}	1.84 ± 0.08^{b}	64.2 ± 10.3^{c}
GWC	4.9 ± 0.2^{ef}	1.02 ± 0.03^{b}	1.42 ± 0.14^{a}	298 ± 43.3^{a}	3.24 ± 0.84^{a}	70.9 ± 1.73^{bc}
WBC2	5.7 ± 0.1^{c}	0.90 ± 0.05^{cd}	1.46 ± 0.08^{a}	257 ± 8.66^{b}	3.21 ± 0.81^{a}	78.4 ± 2.36^{ab}
WBC4	5.9 ± 0.1^{b}	1.27 ± 0.05^{a}	1.45 ± 0.03^{a}	205 ± 2.89^{c}	3.16 ± 0.73^{a}	79.7 ± 3.65^{a}

Values shown are means ± standard deviations. Individual letters after the means indicate no significant difference between the corresponding treatments ($P < 0.05$).
Control: without any amendment. PAM: application of 1 kg ha^{-1} PAM. WB2 and WB4: biochar application of 2% and 4%, respectively. GWC: compost application of 1%. CB2 and CB4: co-application of compost (1%) and biochar (2% and 4%, respectively).

the findings of Jien et al. (2015, 2017). The contents of TN and IN were significantly increased by the application of compost without any consideration of biochar application, whereas no effect of PAM or biochar was found, which could be attributed to the considerably lower N content in both PAM and biochar compared to the compost (Table 1). The GWC treatment resulted in the highest IN content in the soil. The co-application of biochar with compost reduced the IN content released from the compost, probably owing to the retardation of OM decomposition and the high nutrient retention capacity of the added biochar.

Compared with the control, the Bray P-1 content was much higher with the compost application with/without biochar addition, whereas biochar treatment had no effect on this and the content with the PAM treatment was significantly lower (Table 3). Accordingly, residual P fertility improvements were found to be governed only by compost application in this study. Similarly, PAM treatment significantly decreased and compost application significantly increased the exchangeable K^+ content of the soils. An increase in K availability was also identified for the WB4 treatment. Therefore, the co-application of biochar and compost resulted in the highest exchangeable K^+. This study demonstrated that the co-application of biochar and compost leads to an increase in soil pH, OC, and exchangeable K^+ and a decrease in IN when compared with application of compost alone. Thus, N availability may be a crucial limiting factor for the productivity of soil treated with co-application of biochar and compost. The same positive effects of co-application of biochar with vermicompost on nutrient retention were also revealed by Doan et al. (2015).

3.4. Productivity of the soils after the erosion experiment

The pot experiment was performed to determine the productivity of the treated soils. Fig. 2 illustrates the effects of the subjected treatments on yields of rape shoot after 28 days. All the treatments increased the yields of rape shoot significantly, based on the fresh and dry weights. PAM has been considered to have no toxicity to plants (Seybold, 1994). In the current study, the PAM treatment significantly increased rape yields compared with the control. Because PAM did not improve the soil chemical properties and even decreased the available P and K (Table 3), the enhanced rape growth can be attributed to the PAM-induced improvement of physical properties. For example, PAM can increase the hydraulic properties of soil via flocculation of clay and, therefore, more soil water, carrying N, P and K, can reach the plant root system. This may be a reason why the decreasing concentrations of available P and K due to PAM addition did not inhibit the plant growth in this study.

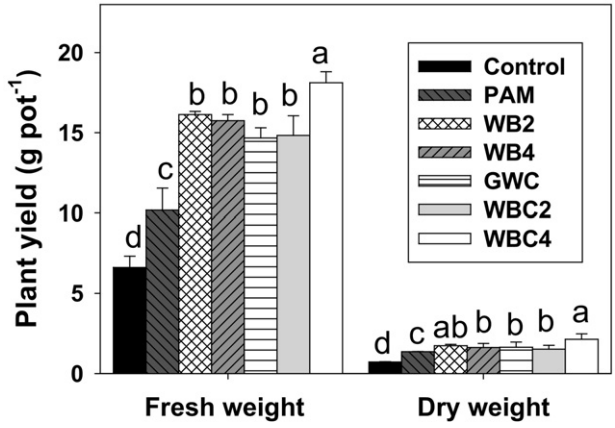

Fig. 2. The 28-d yields of rape shoots cultivated after the soil erosion experiments. Control: without any amendment. PAM: application of 1 kg ha^{-1} PAM. WB2 and WB4: biochar application of 2% and 4%, respectively. GWC: compost application of 1%. WBC2 and WBC4: co-application of compost (1%) and biochar (2% and 4%, respectively). The values of the bars below a same lowercase letter are not significantly different ($P < 0.05$).

Nonetheless, the yield from the PAM-treated soil was still lower than that from the other amendment-treated soils because PAM does not have sufficient soil nutrients for plant growth. As mentioned, the co-application of biochar and compost might limit N availability for plant growth. However, the WBC4 treatment resulted in the highest yield, approximately 2.8 times higher than that of the control. The improvement in rape growth in the amendment-treated soil compared with that in the control soil was a result of the overall effect of the amendment on the soil's physical, chemical, and biological properties.

Conclusions regarding the effect of biochar application in soils on plant yield have been highly variable (Jones et al., 2012; Uzoma et al., 2011). This variability is due to the different compositions and structures of biochar that have been used, and these properties largely depend not only on its pyrolysis conditions and initial feedstock (Kloss et al., 2012) but also on soil properties (Jien and Wang, 2013). Our results confirmed the potential of WB for improving the agricultural performance of low-fertility tropical soil based on a 1-year experiment. The positive effect of biochar application on crop growth and yield has been previously reported (Chan et al., 2007; Lehmann et al., 2003). Lehmann et al. (2003) revealed an increase in plant productivity after biochar application and attributed this to an increase in the soil's available nutrients. In this study, biochar application did not substantially increase available nutrients, but rape growth was enhanced. Biochar has various effects on soil properties such as physical and biological properties, not only on available nutrients for plant growth. In an earlier incubation experiment, the driftwood-generated biochar did improve chemical, physical, and biological properties of the soil used here (Jien and Wang, 2013). In this study, an overall enhancing effect of BC application on plant growth was observed, indicating that available nutrients were not the limiting factor, whereas the improvement of other soil properties masks the passable effects of changes in available nutrients. Furthermore, with the same level of soil TN, the IN decreased but may remain sufficient for rape growth under the co-application of biochar and compost, indicating that N was conserved without an inhibitory effect on rape growth.

The incorporation of biochar into soil significantly affected the concentration of N in the resultant rape shoots, as identified in Table 4. However, no consistent result was revealed regarding biochar application. The lower N concentration in rape shoots may have been the result of a dilution effect of increased yields. In comparison, the effects of the amendments on total N uptake were similar to their effects on rape yields. The N uptake in rape shoots ranged from 15.4 to 35.7 mg pot^{-1}. Biochar co-application with compost decreased the IN content of the soil compared with application of compost alone (Table 2), but the total N uptake increased. Furthermore, application of PAM, biochar, and compost all increased the total N uptake of rape shoots, which was addressed by the WBC4 treatment, indicating that all the amendments facilitated N absorption by the rape. This result was consistent with those of Bruun et al. (2014) and Jones et al. (2012) who indicated that an increase of crop yield in biochar-amended soil might be due to a better-developed root system and better soil solution flow caused by the amendment application. In the current study, the nutrient availability of amendment-treated soils was not the major factor affecting rape growth; physical effects may have been the dominant factors and should be further studied in the future.

4. Conclusions

In this study, the effects of PAM, biochar, compost, and their co-applications on soil properties, runoff water, soil loss, and nutrient loss were evaluated under natural rainfall conditions for a year. The rape productivity was also investigated through a pot experiment. Biochar application decreased the amount of runoff water and the N and P losses via runoff, increased soil pH, OC content, and K^+ availability, enhanced rape growth, and aggravated soil erosion during severe rainfall events. Compost application decreased the amounts of water and soil lost via

Table 4
Nitrogen uptake by rape shoots as affected by the amendments.

Treatment	N content	Total N uptake	Increased N uptake by amendment	N efficiency of amendment
	g mg^{-1}	g pot^{-1}	g pot^{-1}	%
Control	21.3 ± 1.7[a]	15.4 ± 0.9[d]	–	–
PAM	17.5 ± 3.6[ab]	20.8 ± 0.4[c]	–	–
WB2	16.5 ± 1.0[c]	28.7 ± 0.3[ab]	13.3	15
WB4	21.2 ± 2.3[a]	34.7 ± 9.1[a]	19.3	11
GWC	17.4 ± 0.9[bc]	28.7 ± 7.1[ab]	13.3	2.4
WBC2	17.6 ± 2.4[ab]	26.6 ± 0.6[b]	11.2	1.7
WBC4	16.7 ± 0.1[c]	35.7 ± 5.7[a]	20.3	2.8

Values shown are means ± standard deviations. Individual letters after the means indicate no significant difference between the corresponding treatments ($P < 0.05$).
Control: without any amendment. PAM: application of 1 kg ha^{-1} PAM. WB2 and WB4: biochar application of 2% and 4%, respectively. GWC: compost application of 1%. CB2 and CB4: co-application of compost (1%) and biochar (2% and 4%, respectively).
PAM has extremely low N content, and therefore no calculations were made for PAM.
N efficiency equals to the total N uptake by grape divided by total N added to the soil.

runoff; however, soil OC content, total N content, nutrient availability, and rape productivity were increased. The co-application of biochar and compost, especially the WBC4 treatment, had entirely positive effects on tested parameters, thereby resulting in the highest rape productivity among all tested treatments. The co-application of compost and biochar can be used for soil-water conservation in terrestrial barren soils as an alternative to synthetic compounds like PAM.

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